

R&D Status of a gas-compressor based two-phase CO₂ cooling system for FPCCD Vertex Detector

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Fine pixel CCD (FPCCD) is one of the candidate sensor technologies for the vertex detector used for experiments at the International Linear Collider (ILC). FPCCD vertex detector is supposed to be cooled down to -40°C for improvement of radiation immunity. For this purpose, a two-phase CO₂ cooling system using a gas compressor for CO₂ circulation is being developed at KEK. The status of this R&D is presented in this article.

1 Introduction

There are many sensor technologies proposed for the use in the vertex detector for experiments at the International Linear Collider (ILC) [1]. Fine pixel CCD (FPCCD) is one of the candidates [2]. Due to its small pixel size of $\sim 5\ \mu\text{m}$, FPCCD vertex detector can offer very good impact parameter resolution and excellent two-track separation capability. FPCCD sensors will be read out in $\sim 200\ \text{ms}$ between bunch trains. Because there is no beam crossing during the readout, FPCCD sensor option is completely free from the RF noise caused by the very short bunches of the beam. One drawback of FPCCD sensors is relatively poor radiation immunity, particularly large charge transfer inefficiency (CTI) due to radiation induced trap levels.

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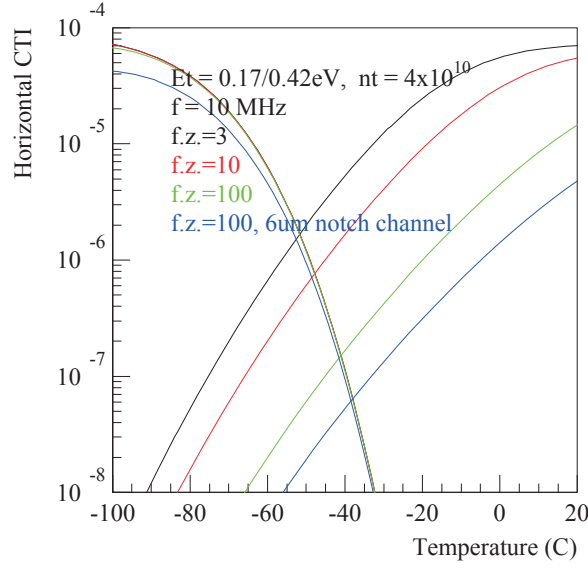


Figure 1: Results of a simple simulation of CTI with trap levels of 0.17 eV and 0.42 eV based on Shockley-Read-Hall theory. With fat-zero charge injection of 100 electrons and notch channel, $\sim -40^{\circ}\text{C}$ is the optimum operation temperature.

CTI of FPCCD due to radiation damage is a function of temperature. A simple simulation of CTI based on Shockley-Read-Hall theory shows that around -40°C is the optimal operating temperature as shown in Figure 1. To achieve this cooling temperature, two-phase CO_2 cooling system seems most suited.

2 Advantages of two-phase CO_2 cooling system

In cooling systems using two-phase coolant, the cooling temperature is controlled by controlling the pressure of the two-phase coolant. Because the heat load is consumed only for evaporation of the coolant, the cooling temperature is constant along the cooling tube. Perfluorocarbon (PFC) such as C_2F_6 has been also used as two-phase coolant for detector cooling systems, for example ATLAS SCT [3]. Compared with PFC, CO_2 has several advantages. Table 1 shows properties of CO_2 and PFC. Latent heat of CO_2 is much larger than that of PFC. Because the pressure of two-phase CO_2 is higher than that of PFC at the same temperature, CO_2 has less temperature drop due to pressure drop along the cooling tube, and less evaporated gas volume than those of PFC. Thanks to these properties, we can use thinner cooling tube for two-phase CO_2 than PFC. Outer diameter of 2 mm or less is good enough for the cooling tube of FPCCD vertex detector.

Because heat sources of FPCCD vertex detector locate mainly at both ends of ladders (on-chip amplifiers and front-end ASICs), cooling at both ends of ladders through the ladder base made of carbon fiber reinforced plastic (CFRP) sheet and endplates on which cooling tube is attached is an attractive solution. The support shell including the end-

	CO ₂	C ₂ F ₆	C ₃ F ₈
Latent heat @−40°C [J/g]	321	~ 100	~ 110
Triple point [°C]	−56.4	−97.2	−160
Critical point [°C]	31.1	19.7	71.9
Pressure @−40°C [MPa]	1	~ 0.5	~ 0.1
Global warming potential	1	12200	8830

Table 1: Properties of several kinds of two-phase coolant.

plate is enclosed in a cryostat made of heat insulating material. The return line of CO₂ will be used to cool the electronics (clock drivers and data compression circuits) placed outside the cryostat. The power consumption of the FPCCD vertex detector will be less than 100 W inside the cryostat and about 200 W/side for the electronics outside the cryostat. Additional material budget due to attached cooling tube of 2 mm ϕ made of Titanium would be only 0.3% X_0 if averaged over the end-plate.

Gas cooling is a possible alternative. However, if we try to cool this vertex detector with cold air or nitrogen gas, the flow rate will be quite large. As a consequence, vibration of the ladders could be caused. Much thicker transfer tube than two-phase CO₂ cooling is necessary for gas cooling, which requires more dead space between forward tracking discs (FTD) and the beam pipe. In addition, constant temperature cooling is almost impossible in case of gas cooling.

3 Gas-compressor based cooling system

Detector cooling systems using liquid pump for circulation of two-phase CO₂ have been developed by several groups [4, 5]. In such a “pump-based system”, CO₂ is liquefied at temperature below the cooling temperature. The temperature of circulating CO₂ is below or at cooling temperature. Therefore, very tight thermal insulation is required for the whole system, including the transfer tubes and the liquid pump. An expensive low-temperature chiller is necessary for liquefaction if the cooling temperature as low as −40°C has to be achieved. A sophisticated “two-phase accumulator” has to be adopted for pressure (and temperature) control of the two-phase CO₂ for the pump-based system.

Our R&D goal is to develop a two-phase CO₂ cooling system using a gas compressor, rather than a liquid pump, for circulation of CO₂. Figure 2 shows schematic diagrams of a pump-based system and a gas-compressor based system. In the gas-compressor based system, CO₂ gas is liquefied by a condenser at near room temperature after compression. The liquid CO₂ is transferred to a heat exchanger near the detector through a transfer tube. The long transfer tube between the liquefier plant and the heat exchanger can be at near room temperature. At the heat exchanger, the liquid CO₂ is cooled down to the detector cooling temperature by the returning two-phase CO₂. Then, the pressure of the CO₂ is decreased by a needle valve (or a capillary tube). The cooling is achieved basically by the latent heat (evaporation) of the returning two-phase CO₂, rather than the Joule-Thomson effect. The two-phase CO₂ is completely evaporated by a heater,

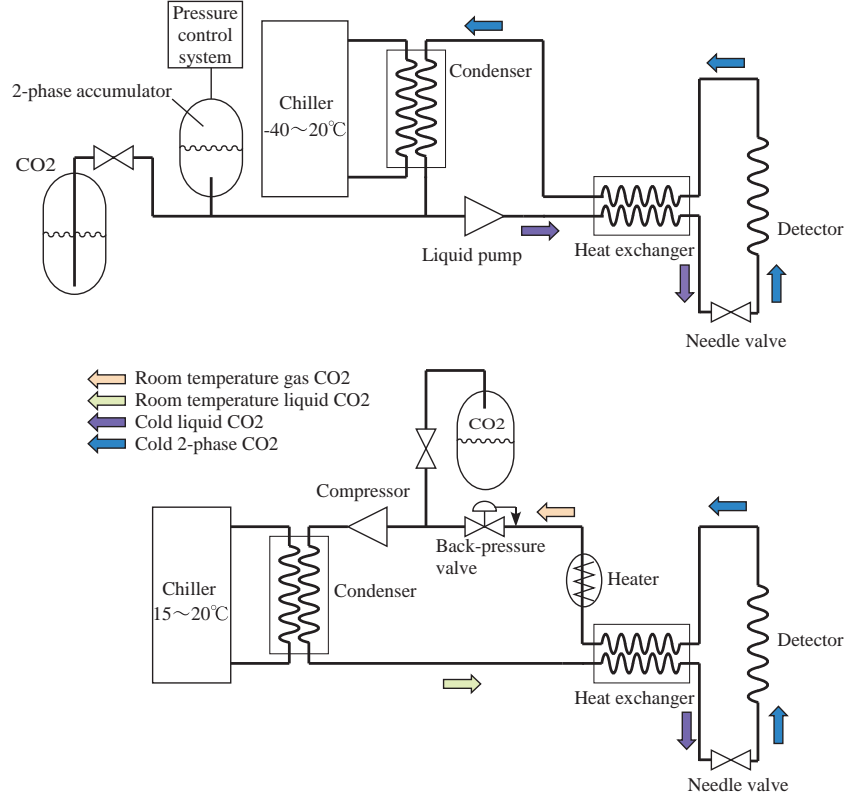


Figure 2: Schematic diagrams of a pump-based cooling system (top) and a gas-compressor based cooling system (bottom).

and goes back to the liquefier plant. The pressure of the two-phase CO₂ is controlled by a back pressure valve in the liquefier plant.

The gas-compressor system has several advantages over the pump system. Because CO₂ is liquefied at near room temperature, we don't need an expensive low temperature chiller. Cooling water near room temperature is enough for the liquefaction. In case of ILC experiment, such cooling water must be available in the detector hall. We don't need strict thermal insulation for long transfer tubes between the liquefier plant and the detector. Flexible transfer tubes off-the-shelf can be used for this purpose. These tubes can be placed on the cable chain supposed to be used for push-pull operation of ILC detectors [1].

4 Construction of a prototype

Several prototypes of the two-phase CO₂ cooling system have been constructed at KEK [6–8]. The latest prototype consists of three units; a liquefier unit, a flow meter unit, and a cooling unit. Figure 3 shows a simplified schematic diagram of the prototype system. Three units are connected with metal-core flexible tubes (1/4 inch

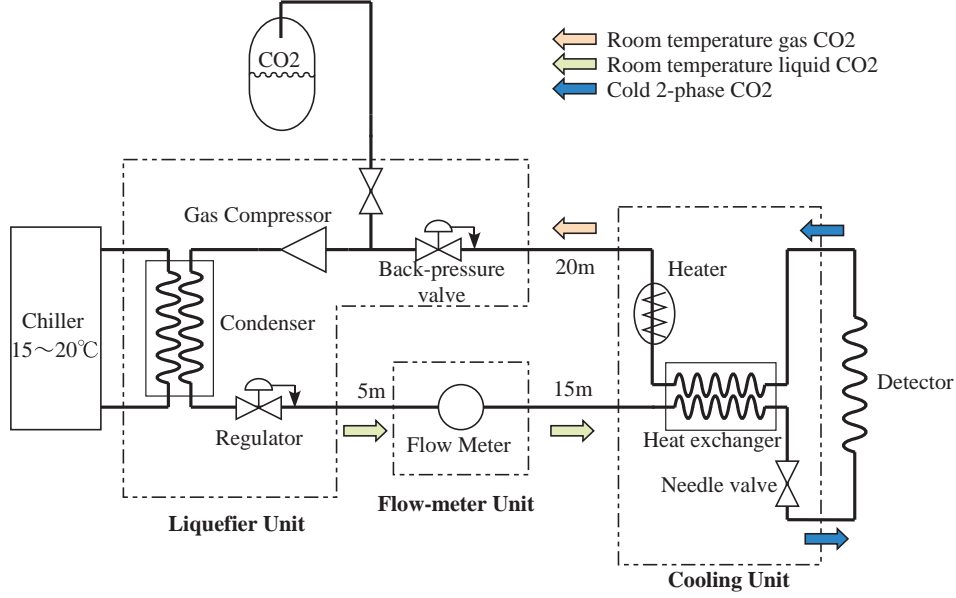


Figure 3: Schematic diagrams of the prototype cooling system.

for liquid, 3/8 inch for gas). As a gas compressor, Haskel gas booster AGD-7 is used. This compressor is a reciprocating type, and driven by compressed air. The exhausted air is used for cooling of gas cylinder of the compressor.

The phase diagram of the system in an ideal operating condition is shown in Figure 4. The expected cooling power at -40°C is 200 J/g. The actual cooling power has been measured using dummy load by looking at the dry-out point where the temperature of CO₂ starts increasing. The two-phase CO₂ with flow rate of 1.4 g/s at cooling temperature of -40°C has dried out with 170 W dummy load power, which is significantly less than the expected cooling power of 280 W ($=200 \text{ J/g} \times 1.4 \text{ g/s}$). The reason of this deficit of the cooling power is presumably heat load of the transfer tube and other low temperature part. This measurement was done at the ambient temperature of 27°C , while the temperature of the liquid CO₂ was 15°C .

Pressure drop in the metal core flexible tubes was one of concerns because inner wall of the tubes has corrugated structure. The pressure drop has actually measured for several values of the flow rate. The measured pressure drop is reasonably low. At low flow rate ($< 1.4 \text{ g/s}$), the pressure drop is less than resolution of the digital pressure gauge. At high flow rate ($> 2 \text{ g/s}$), the pressure drop is dominated by the flow meter for liquid, and still less than the resolution of the pressure gauge for gas.

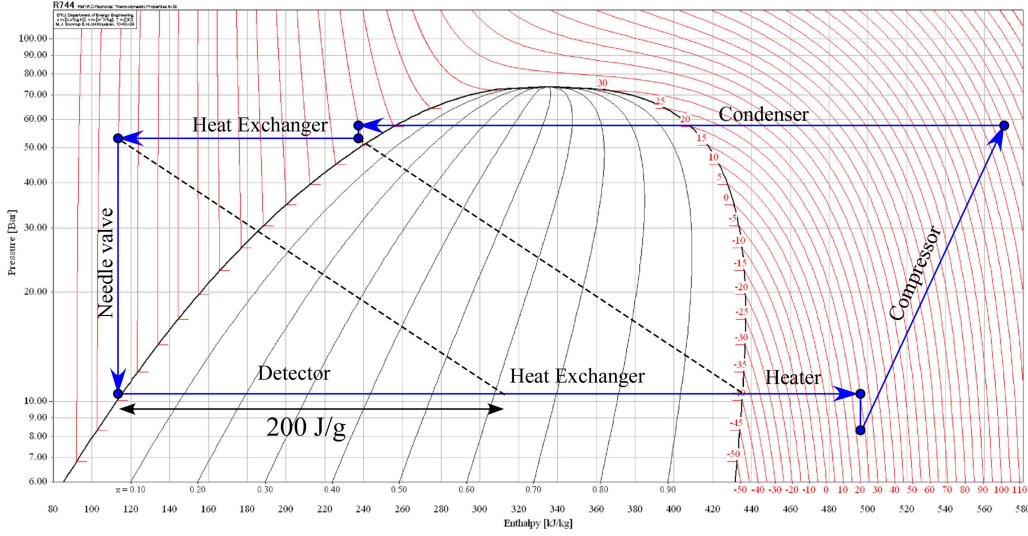


Figure 4: Phase diagram (p-H curve) of the cooling system in an ideal operation condition.

5 Further R&D

5.1 Pressure control

In the prototype cooling system, pressure of the two-phase CO₂ is manually controlled by a back-pressure valve. This method is however somewhat unstable and time consuming for adjustment. To overcome this disadvantage, we plan to replace the manual back-pressure valve with an automatic pressure controller. We have tested a commercially available pressure controller, Bronkhorst P-702CV. Using this controller, the back pressure can be controlled by external voltage setting.

We have studied this pressure controller by inserting it in the return gas line between the cooling unit and the liquefier unit. The back-pressure valve in the liquefier unit was set at the lowest pressure. Figure 5 shows the result of the measurement of the setting voltage, pressure and temperature of the two-phase CO₂, and flow rate of CO₂. It can be seen that quick and stable control of the pressure and the temperature is achieved.

5.2 O-ring material

O-rings made of elastomer are used for the gas compressor and safety valves in our system. Degradation of the O-rings called as explosive decomposition (ED) was seen in these O-rings, and caused gas leak. Explosive decomposition, also called as rapid gas decomposition, is a mechanism of degradation in elastomer due to rapid decompression of gaseous media. At high pressure environment, CO₂ gas immigrates into elastomer.

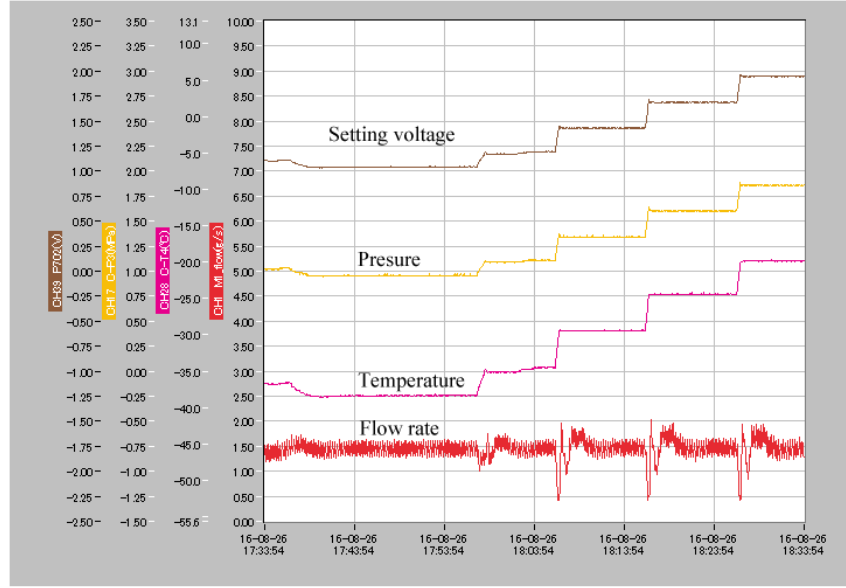


Figure 5: Setting voltage for the pressure controller, and the response of pressure and temperature of two-phase CO₂ to the setting voltage. The flow rate is also shown.

When the pressure is reduced suddenly, CO₂ dissolved inside the elastomer comes out as micro bubbles, expands, and damage the elastomer from inside.

In order to mitigate the risk of gas leak due to ED, we can replace the safety valves with metal-seal safety valves. For the gas compressor, we should find out better material for O-rings. We have constructed O-ring ED test apparatus, and plan to test several kinds of O-rings with different Shore durometer hardness and different materials such as Kalrez, Chemraz, and so on. In the worst case, frequent overhaul of the gas compressor would be the solution.

5.3 Other R&D issues

In the present prototype system, a very massive stainless-steel plate heat exchanger is used. We plan to develop a very low mass heat exchanger which can be placed inside the detector. As a candidate, a heat exchanger made of double-layer tube will be studied.

The size of the liquefier unit for the present prototype is quite large ($\sim 1 \text{ m} \times 1 \text{ m} \times 2 \text{ m}$). We would like to develop a more compact liquefier unit. The gas booster used in the liquefier is quite noisy. Sound insulation should be implemented in the next prototype of the liquefier unit.

The present prototype is controlled manually. The remote control system using a programmable logic controller (PLC) is one of the R&D issues.

On the detector side, thermal contact between the cooling tube and the end-plate of the vertex detector, and between the end-plate and the ladders has to be studied.

6 Summary

We have successfully developed a prototype of two-phase CO₂ cooling system using a gas compressor for CO₂ circulation. Cooling power of the system has been measured at the cooling temperature of -40°C , and a satisfactory results have been obtained for FPCCD vertex detector cooling. On the other hand, degradation problem of O-rings exists, and has to be solved. There are still many R&D issues to be accomplished to realize the practical cooling system.

Acknowledgments

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